JENA ECONOMIC RESEARCH PAPERS

2014 – 027

Auctions and Leaks: A Theoretical and Experimental Investigation

by

Sven Fischer
Werner Güth
Todd R. Kaplan
Ro'i Zultan

www.jenecon.de

ISSN 1864-7057

The JENA ECONOMIC RESEARCH PAPERS is a joint publication of the Friedrich Schiller University and the Max Planck Institute of Economics, Jena, Germany. For editorial correspondence please contact markus.pasche@uni-jena.de.

Impressum:

Friedrich Schiller University Jena
Carl-Zeiss-Str. 3
D-07743 Jena
www.uni-jena.de

Max Planck Institute of Economics
Kahlaische Str. 10
D-07745 Jena
www.econ.mpg.de

Auctions and Leaks:
A Theoretical and Experimental Investigation

Sven Fischer*, Werner Güth†, Todd R. Kaplan‡ & Ro'i Zultan§

This version: November 5, 2014

We study first- and second-price private value auctions with sequential bidding where second movers may discover the first movers bids. There is a unique equilibrium in the first-price auction and multiple equilibria in the second-price auction. Consequently, comparative statics across price rules are equivocal. We experimentally find that in the first-price auction, leaks benefit second movers but harm first movers and sellers. Low to medium probabilities of leak eliminate the usual revenue dominance of first-price over second-price auctions. With a high probability of a leak, second-price auctions generate higher revenue.

Keywords: auctions, espionage, collusion, laboratory experiments.

JEL: C72, C91, D44

*Max Planck Institute of Economics, Kahlaische Str. 10, 07745 Jena, Germany and Max Planck Institute for Research on Collective Goods, Bonn, Germany. fischer@coll.mpg.de, Tel: +49(0)3641-686-641, corresponding author.

†Max Planck Institute of Economics. gueth@econ.mpg.de, Tel: +49(0)3641-686-621, Fax: +49(0)3641-686-667.

‡University of Exeter, Exeter, EX4 4PU, UK, and University of Haifa, Mount Carmel, Haifa 31905, Israel. Dr@ToddKaplan.com, Tel: +44-4392-263237, Fax: 1-530-871-6103.

§Ben Gurion University of the Negev, P.O.B. 653, Beer-Sheva 84105, Israel. zultan@bgu.ac.il, Tel: +972(0)86472306

1. Introduction

Most theoretical and experimental studies of sealed-bid auctions assume simultaneous bidding (Kagel, 1995; Kaplan and Zamir, 2014). Nonetheless, in government procurement or when selling a privately owned company (such as an NBA franchise), the auctioneer may approach bidders separately, or bidding firms/groups may go through a protracted procedure of authorizing the bid—implying a sequential timing of decisions (cf. Bulow and Klemperer, 2009).[1] This paper studies situations in which bidding is sequential and information leaks about earlier bids are possible.

We consider independently and identically distributed private value auctions with two bidders and an exogenous and commonly known probability of the first bid being leaked to the second bidder ahead of her bid. We characterize the equilibria for the first- and second-price rule as a function of leak probability. For uniformly distributed valuations, the unique equilibrium in first-price auctions is invariant with leak probability. In second-price auctions, multiple equilibria exist, differing in how the second bidder reacts when learning that the first bid exceeds her own value—In which case the second bidder's decision essentially allocates the surplus between first bidder and seller.

We call second bidders in this situation *rational losers*, because while they lose the auction, their bidding behavior is rational given that the other bid is above their value.[2] Depending upon the rational loser behavior, there are several focal equilibria among the equilibria of the second-price auction: (a) a truthful bidding equilibrium—equivalent to the equilibrium of the simultaneous auction—in which the rational loser bids his true value; (b) a spiteful bidding equilibrium, in which the rational loser bids close to the first bidder's bid; and (c) a cooperative equilibrium, in which the optimal loser bids at the reserve price.

[1] We acknowledge that the auctioneer may return to a bidder for a revised bid. It may, however, be prohibitively expensive and time consuming for a bidding firm to generate a new bid. Government procurement auctions often employ *best and final offer* procedures, meaning that once initial bids are collected, bidders are requested to submit a final price bid. In such cases, our theoretical model and experiment can be viewed as reflecting this (commonly known to be) final stage of the auction.

[2] It may be still rational to win the auction if the bidder enjoys a *joy of winning*. Joy of winning, however, does not provide a good description of behavior in experimental auctions (Levin et al., 2014).

In the field, the probability of a leak can be manipulated in various ways. Early movers can actively leak information; late movers can engage in industrial espionage; auctioneers may prevent leaks through legal action or by imposing strict timing of bids. As a first step in studying these environments, we set the leak probability exogeneously and analyze its effects on allocations.

In the equilibrium of the first-price auction, leaks benefit the second bidder who, when observing a first bid lower than her value, can win the auction paying only a price equal to the first bid. Thus, compared to simultaneous bidding, second bidders pay a lower price when having the higher value. Furthermore, as the equilibrium bid of the first bidder is below her value, second movers may win even when holding a lower value. The upshot is that an increase in the probability of a leak increases the expected revenue of the second bidder while reducing that of the first bidder, as well as seller surplus and efficiency.

In the second-price auction, outcomes strongly depend on the selected equilibrium. With truthful bidding, the information revealed through the leak is ignored, hence buyer surplus, seller revenue, and efficiency are not affected by leaks. In all other equilibria, efficiency decreases with increasing leak probability, with the cooperative equilibrium performing worst in terms of seller revenue and efficiency. In the cooperative equilibrium, first bidders earn more and second bidders less than in the truthful bidding equilibrium, whereas the opposite holds for the spiteful bidding equilibrium. These differences with respect to truthful bidding increase with leak probability.

Whether the parties or a social planner should prefer the first-price or second-price rule depends not only on the equilibrium selection in the second-price auction, but in some cases also on the leak probability. For example, assume that bidders coordinate on the cooperative equilibrium in the second-price auction. In this case, seller revenue is higher in the first-price auction irrespective of the leak probability. Efficiency, however, is only higher in the first-price auction if the leak probability is above one half, and is otherwise higher in the second-price auction.

We conducted an experiment to test the predictions of the theoretical analysis. The experimental design allows us to explore equilibrium selection in the second-price auction with leaks and to test the effects of the auction mechanism and probability of leak on bidders surplus, seller revenue, and efficiency. The empirical investigation of equilibrium selection is important because, ex ante, it is not clear which equilibrium will be favored as all equilibria have desirable features from the point of view of the bidders. Truthful bidding is simple and frugal as well as ex-ante egalitarian. The cooperative equilibrium maximizes the bidders joint surplus—and hence the total experimental payoff. The spiteful bidding equilibrium maximizes the second bidder's payoff, who is arguably in the best position to affect the equilibrium selection as she is indifferent between the different strategies available to her as a rational loser. Our experimental design manipulates the probability of leak within auction mechanism while keeping the roles fixed. Two additional treatments manipulate the ex-ante symmetry in roles while keeping the probability of leak fixed at one to explore the effect of expected inequality on equilibrium selection in the second-price auction.

In line with equilibrium predictions, first mover bids in the first-price auction treatments do not vary systematically with leak-probabilities. Informed second bidders generally behave rationally, winning the auction if and only if they can gain by doing so. Overall, leaks increase the second bidder's payoff and reduce the first bidder's payoff, seller revenue, and efficiency.

In the second-price auction, rational losers employ different strategies—in most cases (roughly) corresponding to one of the three focal equilibria—with about one third of participants behaving consistently across all rounds. On average, efficiency decreases with leak probability while all other outcomes are not sensitive to it. Without leaks, the first-price auction maximizes the seller's revenue due to bid shading, as is often observed in experimental auctions (e.g., Kagel, 1995). Conversely, when leaks are certain, seller revenue is higher in the second-price auction. Efficiency is slightly higher in the second-price treatments for all leak-probabilities. A secondary hypothesis about how ex-ante equality affects coordination is not supported.

The sequential protocol in auctions has been studied, theoretically and experimentally, in the context of contests (Fonseca, 2009; Hoffmann and Rota-Graziosi, 2012). Although no previous study looked at the effect of equilibrium selection in second-price auctions with sequential moves, this point has been indirectly addressed with regard to ascending bid auctions. Cassady (1967) suggested, based on anecdotal evidence, that placing a high initial bid can deter other bidders from entry, which can be rationalized if participation or information acquisition is costly (Fishman, 1988; Daniel and Hirshleifer, 1998).[3] In our setup, bidding costs would eliminate all but the cooperative equilibrium in the second-price auction and not affect the equilibrium in the first-price auction when bidding costs are very small.

This paper is also related to a large literature on information revelation in auctions (Milgrom and Weber, 1982; Persico, 2000; Kaplan, 2012; Gershkov, 2009). Several papers study revelation of information about the bidders' valuation by the auctioneer (Kaplan and Zamir, 2000; Landsberger et al., 2001; Bergemann and Pesendorfer, 2007; Eső and Szentes, 2007). As in our study, Fang and Morris (2006) and Kim and Che (2004) compare the first-price and second-price mechanisms, but consider revelation of valuations rather than bids. The predictions of Kim and Che (2004) were experimentally tested and corroborated by Andreoni et al. (2007). To the best of our knowledge, this is the first paper analyzing the revelation of actions rather than types in private-values auctions.

We present and analyze the bidding contests in Section 2. The experimental design is described in Section 3. Our findings are discussed in Section 4. Section 5 concludes.

2. The Auction Game and Benchmark Solutions

There are two bidders, 1 and 2, and two time periods. Each bidder i has private value v_i drawn independently from the continuous distribution F on $[0, 1]$, with 0 the exogenously given reservation price of the seller. At time 1, bidder 1, the first mover, submits

[3]See Avery (1998) for an analysis of jump bidding with affiliated values. See also Ariely et al. (2005); Ockenfels and Roth (2006); Roth and Ockenfels (2002) for an analysis of second-price auctions with endogenous timing.

an unconditional bid $b_1(v_1)$. At time 2, with probability p, bidder 2, the second mover, sees b_1 and submits a conditional bid $b_2(b_1, v_2)$ and with probability $1 - p$ does not see b_1 and submits an unconditional bid $b_2(\emptyset, v_2)$. In case of a tie, we assume throughout that bidder 2 wins. The allocation and payments are determined either by the first-price (FPA) or second-price auction (SPA).

2.1. First-Price Auction

To solve the first-price auction, first look at bidder 2's optimal bid $b_2(b_1, v_2)$ after seeing b_1, bidder 1's bid. If $b_1 \leq v_2$, bidding $b_2(b_1, v_2) = b_1$ would win at the lowest price possible. For $b_1 > v_2$, bidder 2 underbids b_1. Thus, in equilibrium

$$b_2(b_1, v_2) \begin{cases} = b_1 & \text{if } b_1 \leq v_2, \\ < b_1 & \text{otherwise.} \end{cases} \tag{1}$$

When chance prevents an information leak, assume $b_1(v_1)$ and $b_2(\emptyset, v_2)$ to be monotonically increasing in v_1 and v_2 with inverse $v_1(b_1)$ and $v_2(b_2)$, respectively. Assuming risk neutrality, an uninformed bidder 2 chooses b_2 to maximize

$$\pi_2(v_2) = \max_{b_2} F(v_1(b_2))(v_2 - b_2). \tag{2}$$

Similarly, bidder 1 tries to maximize

$$\pi_1(v_1) = \max_{b_1} [pF(b_1) + (1 - p)F(v_2(b_1))](v_1 - b_1). \tag{3}$$

The first-order conditions from (2) and (3) are

$$F'(v_1(b_2))v_1'(b_2)(v_2(b_2) - b_2) = F(v_1(b_2)),$$

$$[(1 - p)F'(v_2(b_1))v_2'(b_1) + pF'(b_1)](v_1(b_1) - b_1) = (1 - p)F(v_2(b_1)) + pF(b_1).$$

Proposition 1. *When F is uniform, the unique equilibrium in monotonically increas-*

ing bidding functions of the via anticipating (1) truncated game is $v_1(b_1) = 2b_1$ *and* $v_2(b_2) = 2b_2$.

Proof. When F is uniform, the first-order conditions reduce to

$$v_1'(b_2)(v_2(b_2) - b_2) = v_1(b_2),$$

$$[(1-p)v_2'(b_1) + p](v_1(b_1) - b_1) = (1-p)v_2(b_1) + pb_1,$$

with the unique solution $v_1(b_1) = 2b_1$ and $v_2(b_2) = 2b_2$. □

Thus, in equilibrium neither first nor conditional or unconditional second bids are affected by leak probability. However, leaks can affect who wins and how much bidders earns (see Appendix A).

Corollary 1. *For F uniform and the first-price auction, bidder 1, from an ex ante point of view, earns* $\frac{1}{6} - \frac{p}{12}$*, and bidder 2 the amount* $\frac{1}{6} + \frac{p}{8}$*; the seller's expected revenue is* $\frac{1}{3} - \frac{p}{12}$*, implying an efficiency loss of* $\frac{p}{24}$.

2.2. Second-Price Auction

For the second-price auction, there exist multiple equilibria in weakly undominated strategies when $p > 0$. When bidder 2 does not see 1's bid, to bid truthfully $b_2(\emptyset, v_2) = v_2$ is weakly dominant. If bidder 2 observes that b_1 exceeds v_2, she will want to underbid b_1. We call such bidder 2 a "*rational loser*" and denote the according bid by $g(b_1, v_2)$, which satisfies the following property.

Property (P1): $g(b_1, v_2) < b_1$ for all $v_2 < b_1$.

If bidder 2 observes $b_1 < v_2$, she will want to bid above b_1, with v_2 being a focal strategy. Altogether the equilibrium bid of an informed bidder 2 is given by

$$b_2(b_1, v_2) = \begin{cases} v_2 & \text{if } b_1 \le v_2, \\ g(b_1, v_2) & \text{otherwise.} \end{cases} \tag{4}$$

Anticipating this, bidder 1 maximizes

$$p\int_0^{b_1}(v_1 - g(b_1, v_2))dF(v_2) + (1-p)\int_0^{b_1}(v_1 - v_2)dF(v_2).$$

If $g(b_1, v_2)$ is continuous, differentiable, and weakly increasing in both arguments, the first-order condition (valid for $b_1 \in [0, 1)$) becomes

$$v_1 = p \cdot g(b_1, b_1) + (1-p)\cdot b_1 + \frac{p}{F'(b_1)} \cdot \int_0^{b_1} \frac{\partial g(b_1, v_2)}{\partial b_1} dF(v_2). \tag{5}$$

Proposition 2. *If $g(b_1, v_2)$ is continuous, differentiable, weakly increasing in both arguments, and satisfies P1, then the bid functions $b_1(v_1)$, $b_2(\emptyset, v_2) = v_2$ and $b_2(b_1, v_2)$ as defined by (4) form an equilibrium if $b_1(v_1)$ is consistent with (5).*

From Proposition 2 we see that there are multiple equilibria depending on $g(b_1, v_2)$, the conditional bid of a rational loser. In the following, we describe three focal equilibria: in *SP-Truthful*, a rational loser bids her true value $g(b_1, v_2) = v_2$; in *SP-Spiteful*, she leaves as little for bidder 1 as possible by slightly underbidding him with $g(b_1, v_2) \nearrow b_1$; in *SP-Cooperative*, she favors bidder 1 and harms the seller by $g(b_1, v_2) = 0$.

Corollary 2. *In all equilibria of SPA, an uninformed 2 bids $b_2(\emptyset, v_2) = v_2$ and bids of an informed 2 satisfy (4) and P1. Bids of bidder 1 depend on $g(b_1, v_2)$, the conditional bid of a rational loser bidder 2, as follows:*

- *In SP-Truthful, $g(b_1, v_2) = v_2$ and $b_1(v_1) = v_1$.*
- *In SP-Spiteful,[4] $g(b_1, v_2) = b_1$ and $v_1 = b_1 + p \cdot \frac{F(b_1)}{F'(b_1)}$, i.e., for F uniform $b_1(v_1) = \frac{v_1}{1+p}$.*
- *In SP-Cooperative, $g(b_1, v_2) = 0$ and $b_1(v_1) = \frac{v_1}{1-p}$ for $v_1 \leq 1-p$ and $b_1(v_1) \leq 1$ otherwise.*

[4]For the existence of a monotonic strategy by bidder 1 in SP-Spiteful, it is sufficient that the reverse hazard rate, $\frac{F'(v)}{F(v)}$, is decreasing.

As p approaches 1 cooperative bidding has bidder 1 bidding 1 (independent of v_2) and bidder 2 bidding 0. The resulting ex-ante expected outcomes are listed in Table 1 (see Appendix B for calculations).

Notice that while we have been treating $g(b_1, v_2)$ as a representation of a pure strategy. It can also represent the expectation of a mixed strategy by bidder 2 or the expectation of several heterogenous strategies used by players in the role of bidder 2. For instance if fraction α play the strategy of *SP-Spiteful* and $1 - \alpha$ play the strategy of *SP-Cooperative*—or any strategy where the expectation of bidder 2's strategy is $\alpha \cdot b_1$—then any equilibrium will have the first bidder will behave as if bidder 2 is playing $g(b_1, v_2) = \alpha \cdot b_1$.

Corollary 3. *In all equilibria of SPA where the expected strategy of the second bidder is given by (4) and $g(b_1, v_2) = \alpha \cdot b_1 + \beta \cdot v_2$ (where $\alpha, \beta \geq 0$ and $\alpha + \beta \leq 1$), we have the first bidder choosing b_1 according to $v_1 = (1 - p + (\alpha + \beta) \cdot p)b_1 + \alpha \cdot p \cdot \frac{F(b_1)}{F'(b_1)}$. In the uniform case, bidder 1's equilibrium strategy reduces to $b_1(v_1) = \frac{v_1}{1-p+(2\alpha+\beta)p}$.*

From Corollary 3, we see that in the uniform case $g(b_1, v_2)$ can be reduced to a linear function αb_1, where α incorporates the expected term $\mathbb{E}(\beta \cdot v_2) = \frac{\beta}{2}$. When $\alpha = 1/2$, there is truthful bidding by bidder 1. We also see that as α or β is increasing, the bidding by bidder 1 becomes less aggressive. This is true not only when F is uniform, but for general F (under a decreasing reverse hazard rate). We also see that this is true more generally when comparing equilibria.

To see this, let us compare two equilibria, a and b, based on equilibrium strategies $g^a(b_1, v_2)$ and $b_1^a(v_1)$ for equilibrium a and $g^b(b_1, v_2)$ and $b_1^b(v_1)$ for b. The following proposition holds for any two such equilibria:

Proposition 3. *If F is weakly concave and $\frac{\partial g^a(b_1,v_2)}{\partial b_1} > \frac{\partial g^b(b_1,v_2)}{\partial b_1}$ for all $b_1 \geq 0$, $v_2 \geq 0$, then $b_1^a(v_1) < b^b(v_1)$ for all $v_1 > 0$.*

Proof. The RHS of equation (5) is (i) equal to 0 for $b_1 = 0$, (ii) strictly increasing in b_1, and (iii) strictly larger for g^a than for g^b. Thus, for a particular $v_1 > 0$, the b_1 that equates both sides for g^a is strictly smaller than for g^b. Hence, we have $b_1^a(v_1) < b^b(v_1)$ for all $v_1 > 0$. □

Intuitively, Proposition 3 says that a more aggressive bidder 2 leads to a less aggressive bidder 1.

Table 1: Equilibria and Expected Outcomes for F Uniform on $[0, 1]$.

Environment/Eqm.	$b_1(v_1)$	$g(b_1, v_2)$	Bidder 1	Bidder 2	Seller	Eff. Loss
First Price	$\frac{v_1}{2}$	$\cdot$	$\frac{1}{6} - \frac{p}{12}$	$\frac{1}{6} + \frac{p}{8}$	$\frac{1}{3} - \frac{p}{12}$	$\frac{p}{24}$
SP-Truthtful	v_1	v_2	$\frac{1}{6}$	$\frac{1}{6}$	$\frac{1}{3}$	0
SP-Spiteful	$\frac{v_1}{1+p}$	$\nearrow b_1$	$\frac{1}{6(1+p)}$	$\frac{1+3p(1+p)}{6(1+p)^2}$	$\frac{1+2p}{3(1+p)^2}$	$\frac{p^2}{6(1+p)^2}$
SP-Cooperative	$\frac{v_1}{1-p}$	0	$\frac{1+p+p^2}{6}$	$\frac{1-p}{6}$	$\frac{1-p^2}{3}$	$\frac{p^2}{6}$

3. Experimental Design

We ran six sessions, each with 32 student participants from universities in Jena recruited using ORSEE (Greiner, 2004).[5] Sessions lasted between 90 and 135 minutes. The experiment was conducted using z-Tree (Fischbacher, 2007).

Three sessions implemented the first-price auction and three were run for the second-price auction. Each session had participants matched in pairs over 36 rounds using random stranger rematching. More specifically, the 32 participants were split up in four matching groups of 8 participants each. Participants were only informed about random rematching but not about matching groups. Unannounced to participants, half of them were assigned to role A, and the other half to role B, which remained fixed throughout the session.

In every round, each participant i was assigned a privately known value v_i, drawn independently from the uniform distribution on $[20.00, 120.00]$ insteps of 0.01. Each

[5]The students were recruited from Friedrich Schiller University Jena and University of Applied Science Jena.

round consisted of two stages. In the first stage, a participant could submit an *unconditional bid* (b_1 and $b_2(\emptyset, v_2)$) between 0.00 and 140.00 in steps of 0.01.

After the first stage, with probability p_A participant A would see the bid of participant B in his pair, and with probability p_B participant B would see the bid of participant A in his pair. With the remaining probability, no information was revealed. An informed participant could revise her bid by submitting a *conditional bid* $b_2(b_1, v_2)$. Participants submitted conditional bids in strategy method. I.e., both participants observed the unconditional bid of their opponent, and each participant i such that $p_i > 0$ submitted a conditional bid. Finally, the random draw was realized (if applicable), and participants received feedback about the winner od the auction and their own earnings for the round.

The six leak-probability treatments were varied within subjects across rounds. Participants rotated through six cycles, each consisting of one round per treatment, for a total of 36 rounds. The matching and order of rounds was independently randomized for each matching group and cycle in the FPA sessions, and repeated for the SPA sessions to facilitate comparison across auction mechanisms. Table 2 lists all treatment conditions differing in probabilities p_A and p_B. In *baseline* participants submitted their unconditional bids simultaneously and there were no conditional bids. In the three *one-sided* treatments, role B participants submitted conditional bids, which were implemented with probabilities $1/4$, $1/2$, or $3/4$. That is, role A (B) was equivalent to the first (second) mover position in the underlying extensive form game. In the *two-sided* treatments, both participants submitted conditional bids, of which exactly one was implemented (as $p_A + p_B = 1$). That is, the probability of leak was set to one, and p_A and p_B determined the order of moves in the underlying extensive form game. In the *two-sym*, both participants had an equal probability to be in each position, whereas in *two-asym* the player in role A was more likely to be in the first mover position and vise versa for role B. Participants did not know in advance the different probability combinations nor the cycles structure.[6]

[6]Generally, learning in private value auctions is difficult due to random individual values. The probabilistic conditioning process exacerbates this problem. We reduced the number of fundamentally different tasks an individual faces, thus simplifying the experiment, by assigning the lower probabil-

Table 2: Probability treatments

	Probability	
Treatment	Role A	Role B
Baseline	0	0
one-sided-1/4	0	$1/4$
one-sided-1/2	0	$1/2$
one-sided-3/4	0	$3/4$
two-sym	$1/2$	$1/2$
two-asym	$1/4$	$3/4$

We randomly selected five of the 36 rounds for payment. If the sum in these rounds was negative, they were subtracted from a show-up fee of €2.50 and an additional payment of €2.50 for answering a control questionnaire before the experiment. Participants with any remaining negative balance would be required to work it off, however this never occurred.[7] Experimental currency unit payoffs were converted to money at the end of the experiment at a conversion rate of 1 ECU = €0.13 (around 0.177 USD). On average, participants earned €15.41 in total, exceeding the local hourly student wage of around €7.50.

3.1. Experimental Hypotheses

We first state experimental hypotheses for the main probability treatment conditions, the *baseline* and the three *one-sided* conditions.

Optimality in the last stage of the game implies Hypothesis 1 (see equations (1) and (4)).

Hypothesis 1. *Conditional bids $b_i(b_j, v_i)$ are optimal, i.e.,*

a) in FPA, $b_i(b_j, v_i) = b_j$ if $b_j \leq v_i$ and $b_i(b_j, v_i) < b_j$ otherwise.

b) in SPA, $b_i(b_j, v_i) \geq b_j$ if $b_j \leq v_i$ and $b_i(b_j, v_i) < b_j$ otherwise.

ity of revising a bid to role A.

[7]For this purpose we had a special program prepared in which a participant would have to count the letter "t" in the German constitution, with each paragraph reducing the debt by €0.50.

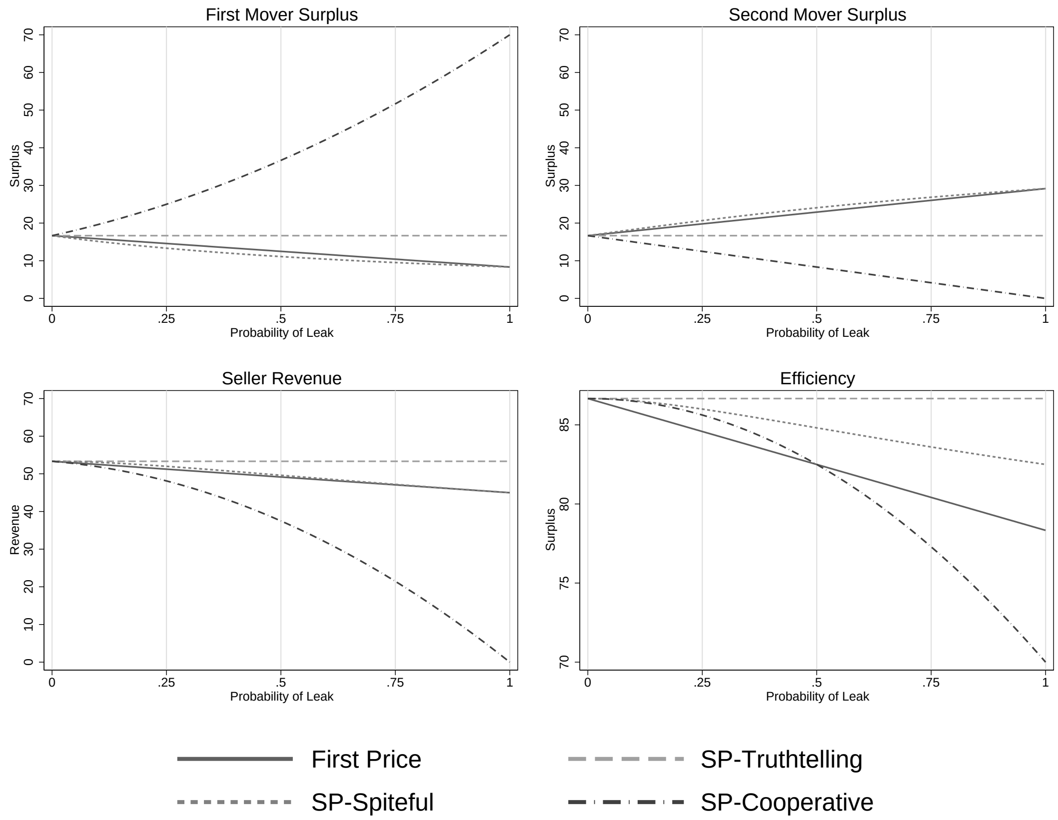

Figure 1: Theoretical Predictions

In FPA and irrespective of optimality in conditional bids, equilibrium unconditional bids b_1 remain unaffected by leak probability, as do unconditional bids of uninformed second movers, i.e., $b_2(\emptyset, v_2)$, in both FPA and SPA (see Proposition 1 and equation (4)). In SPA, unconditional bids of first movers $b_1(v_1)$ depend on how rational losers will behave. In *SP-Cooperative*, first movers bid above their valuation and in *SP-Spiteful* they bid below, with the expected deviations of bids from values increasing with leak-probability. We therefore do not make any directed hypotheses with regard to unconditional bids of first movers in SPA.

Hypothesis 2. *In FPA, unconditional bids $b_1(v_1)$ and $b_2(\emptyset, v_2)$ are unaffected by changes in leak-probability.*

Hypothesis 3. *In SPA, unconditional bids of second movers ($b_2(\emptyset, v_2)$) are unaffected by changes in leak-probability.*

Figure 1 plots the equilibrium expected surplus of first mover (FM) and second mover (SM), the revenue, and efficiency as a function of leak probability, separately by mechanism and (in SPA) type of equilibrium (cf. Table 1). Outcomes for FPA and SP-Spiteful are highly similar throughout.

Hypothesis 4. *In FPA, the second-mover surplus increases and the first-mover surplus, seller revenue, and efficiency decrease with increasing leak probability.*

SP-Truthful is fully efficient, and neither bidder surplus nor revenue are affected by leaks. In SP-Cooperative, leaks have the strongest effects on outcomes (efficiency, revenue, and bidder surplus), including differences in inequality in bidders' earnings. In case of a leak and a low value v_2, the first mover collects his entire value whereas the second mover and seller earn nothing. This outcome is the most unequal and undesirable when assuming pure inequality concerns (see, e.g., Bolton and Ockenfels 2000 and Charness and Rabin 2002). With increasing probability of a leak, the ex-ante payoff expectations of bidders also become increasingly unequal.[8]

Bolton et al. (2005) and Krawczyk and LeLec (2010) show that if a random mechanism selects an otherwise unequal outcome, this becomes more acceptable if ex-ante expected outcomes are more equal. When applied to our setup, this suggests that the unequal outcomes of SP-Cooperative are more acceptable in *one-sided* the less likely they are. Thus, in *one-sided*, participants will less likely coordinate on SP-Cooperative with increasing leak probability. However, since with increasing leak probability also strategic aspects and outcomes change considerably it is difficult to judge how concerns for all these different aspects interact. With the *two-sided* conditions, we induce two strategically identical conditions which only differ in ex-ante symmetry and therefore allow to test whether concerns of ex-ante symmetry or "procedural" fairness affect coordination on one of the equilibria in the SPA.[9] Denote by p_i the probability that bidder i will move

[8] Since the sellers are not participants we assume only inequality of bidders matters.

[9] For a related discussion of procedurally fair auctions, see Güth et al. (2013).

second and observe b_j (with $j \neq i$), and by (p_A, p_B) the pair of leak-probabilities. For example, $(p_A, p_B) = (0, 1/4)$ in *one-sided 1/4*. In *two-asym*, with probability $1/4$ the probability condition is $(1, 0)$, and with probability $3/4$ it is $(0, 1)$. In *two-sym* ex-ante symmetry is guaranteed with equal probabilities of 1/2 for $(1, 0)$ and $(0, 1)$, rendering SP-Cooperation procedurally more fair in *two-sym*.

Hypothesis 5. *In SPA more rational losers select SP-Cooperative in* two-sym *than in* two-asym.

If Hypothesis 5 holds, according to Corollary 2 and Proposition 3, in equilibrium bids by Bidder 1 will be larger in *two-sym* than *two-asym*. However, this requires correct beliefs by bidder 1 participants.

4. Results

Our main research questions pertain to comparisons of the aggregate outcomes—buyers' surplus, seller revenue, and efficiency—across auction mechanisms. However, since these strongly depend on the equilibrium selection in SPA, we begin this section by describing the strategies used by our participants, with special attention devoted to rational losers in SPA. We follow by analyzing the implications for aggregate outcomes.

4.1. Individual Behavior

We analyze individual behavior backwards, starting with the conditional bids of informed second bidders, separately for first and second-price auctions. Figure 2 summarizes types of conditional bids. The left panel shows the proportions of (sub-)optimal and irrational bids for both auction mechanisms. The right panel shows the distributions of types of conditional bids of rational losers in SPA, separately for the one- and two-sided treatments. The figure reveals that (a) clearly irrational behavior—placing a losing bid or losing when a profitable win is possible—is very rare; and (b) the conditional bids by the majority of rational losers are captured by the three focal strategies analyzed in Section 2. These results are described in detail below.

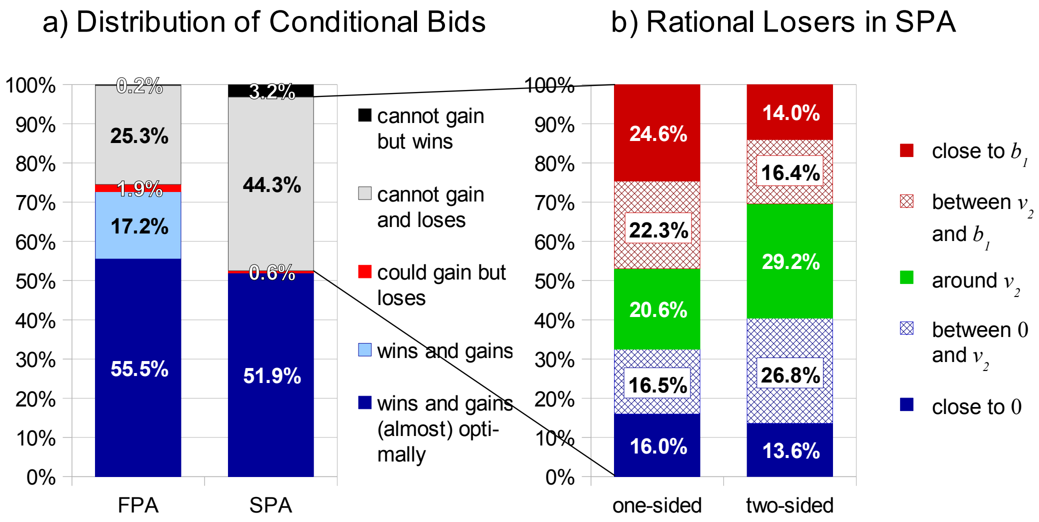

Figure 2: Conditional Bids

Notes: (almost) optimal win in FPA is defined as $b_1 \leq b_2 \leq b_1 + 1$. One observation in FPA was excluded for not fitting any of the categories, as the second bidder won the auction at a loss. The classification of rational losers' bids allow for deviations of 1 ECU (in case of bids around v_2 in both directions). If bid is close to both b_1 and v_2, it is categorized as close to v_2 (1.1% of all cases).

4.1.1. Conditional Bids in FPA

In the first-price auction (see first barplot in Figure 2), in 25.5% of all cases the informed bidder 2 could not gain due to $v_2 \leq b_1$. In almost all of those cases (99.25%) the conditional bid was rational in the sense of $b_2(b_1, v_2) < b_1$. In 74.5% of all observations the conditional bidder could win and gain due to $v_2 > b_1$. In 97.4% of those cases conditional bids were high enough to win the auction. Of those, 18.9% were exactly optimal, 57.5% almost optimal (up to at most 1 ECU), and the remaining 23.6% (17.2% of all observations) were suboptimal in the sense of $b_2(b_1, v_2) \in (b_1 + 1, v_2)$, amounting to an average loss of 16.8 ECU or about 33.5% of maximal possible surplus. Regressions of relative loss, specifically forgone surplus divided by maximal gain on period and leak probability, reveal no dependence on leak probability (coefficient of leak probability: .0115 with $p = .471$) but a significant decrease with experience (coefficient of period:

-.00166 with $p = .018$).[10] Despite some suboptimality, Hypothesis 1a is therefore confirmed.

Result 1. *Conditional bids in FPA secure a gain when possible or guarantee no loss otherwise (97.4% and 99.3% of all cases, respectively). Some bidders do not extract the entire possible gain (independent of leak probability) but less so as they gain experience.*

4.1.2. Conditional Bids in SPA

In 52.5% of all cases, the informed second bidder 2 could gain as $v_2 > b_1$, and in 98.8% of those cases conditional bids would have secured that gain (see second barplot in Figure 2). In 6.7% of the remaining 47.5% of cases with no possibility to gain, conditional bids were too high so that they would have resulted in a loss. On average, this loss amounts to 24.89 ECU. Such mistakes mostly occurred early in the experiment, 50% before Period 11 and 90% before Period 29 (of 36), and were equally likely across leak probability conditions. Thus, Hypothesis 1b is only partly confirmed.

Result 2. *In SPA, when informed second bidders can gain, almost all (99.8%) win the auction. If no gain is possible, there is still non-negligible share of winning conditional bids (6.7%). This , however, mostly happens early in the experiment.*

4.1.3. Rational Losers in SPA

In total, in 44.3% of all cases the informed second bidder had a lower valuation than the first bid ($v_2 < b_1$) and underbid in order to lose.[11] In the right panel of Figure 2 we categorize such conditional bids of "*rational losers*" as follows. We first categorize nearly truthful bids of $b_2(b_1, v_2) = v_2 \pm 1$ as "*around* v_2," all remaining bids less than one as "*close to 0*," and those greater or equal $b_1 - 1$ as "*close to* b_1". Finally, all remaining

[10] Mixed effects regression of relative loss on valuation, leak probability, and period; including random effect on participant nested in matching group effects.

[11] This proportion is less than the 50% expected by chance if first bidders bid truthfully since, in contrast to the overbidding typically observed in second-price auctions, first bidders bid, for strategic reasons, on average less than their value.

bids are either "*between* v_2 *and* b_1," or "*between 0 and* v_2". With 61.2% and 56.8% the majority of all conditional bids of rational losers are close to one of the three focal points in the one- and two-sided treatments, respectively.

Individual Consistency. We generate the distribution of conditional bid types individually for every participant. All except one participant faced this situation at least twice. Of those 95 participants, 27 always reacted with the same type of conditional bid, and a total of 28 (37) chose the same response category at least 90% (80%) of the time. As another test of individual consistency, we regressed the relative conditional bids on a constant with fixed effects participants, resulting in an adjusted $R^2 = 0.406$, a fair share of individual variance.

Stability over Time. Within each treatment the distribution among types of conditional bids vary considerably but mostly unsystematically over the course of the experiment. For a closer analysis of rational loser bids we look at relative conditional bids α defined as the normalized ratio of the conditional bid divided by the observed first bid, i.e. $\alpha_2 = (b_2(b_1, v_2) - 20)/(b_1 - 20)$ (cf. Corollary 3). Figure 3 shows the estimated values of α by treatment and cycle. The figure reveals that relative conditional bids are fairly stable. Mixed effects regressions of relative conditional bids on cycle and value confirm that, except for *one-sided-3/4*, relative conditional bids are stable over time, with overall α estimated at 0.43 with 95% CI [0.35,0.51].[12] When excluding the first cycle, there are no time effects at all.[13] In the following analysis we therefore exclude the data of the first six periods.

Treatment Effects. We test for treatment effects by regressing absolute and relative conditional bids on leak probability, again using a mixed effects regression with random

[12]Model includes constant and valuation, and random effect for participant, nested in random effect on matching group. Coefficient on Period (p-value): *one-sided-1/4*: .00903 ($p = .528$); *one-sided-1/2*: .00738 ($p = .522$) ; *one-sided-3/4*: .0258 ($p = .025$); *two-sym*: .0017 ($p = .896$); *two-asym*: .0011 ($p = 0.894$).

[13]Coefficient on Period (p-value): *one-sided-1/4*: .0277 ($p = .117$); *one-sided-1/2*: .00664 ($p = .648$); *one-sided-3/4*: -.0011 ($p = .924$); *two-sym*: -.01857 ($p = .155$); *two-asym*: -.0162 ($p = 0.181$).

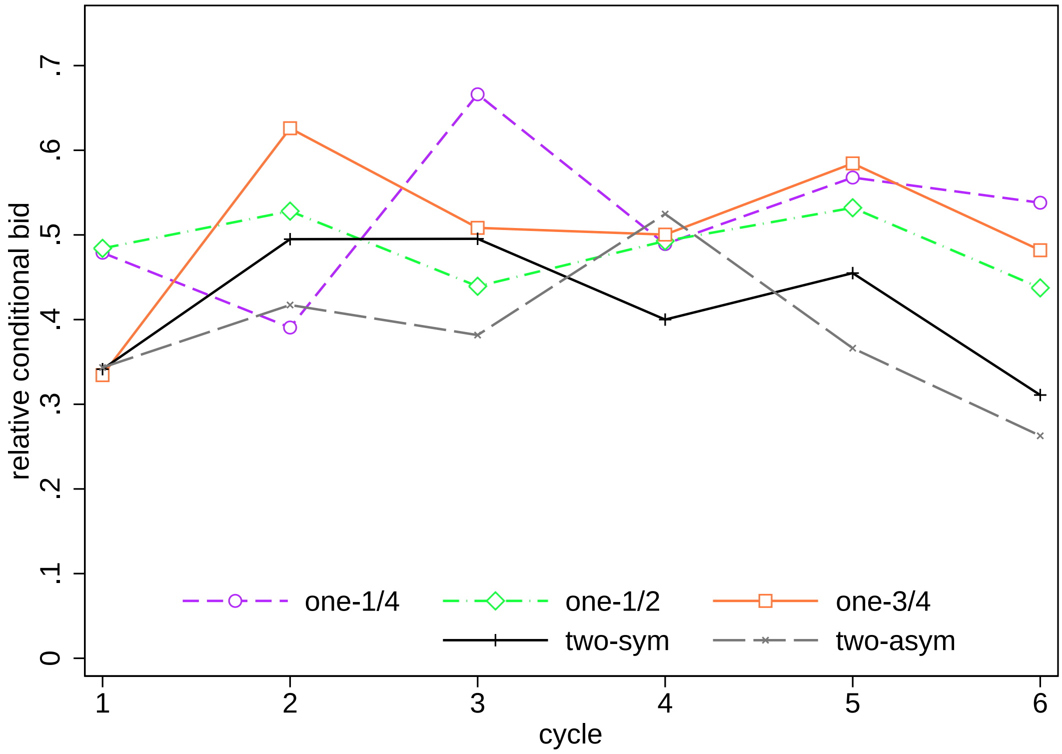

Figure 3: Relative Conditional Bids of Rational Losers in SPA

The figure plots $\frac{b_2(b_1,v_2)}{b_1}$ for rational losers by cycle for different leak probabilities. Despite the heterogeneity of rational loser strategies, rational losers bid on average around 60% of the observed bid across time and leak treatments.

effects on participants, nested in random effects per matching group. Using only data from *one-sided*, leak-probabilities do not affect bids of rational losers (effect of leak probability on relative conditional bid: 0.045, $p = .355$). We summarize

Result 3. *Relative conditional bids of rational losers in SPA are (i) stable across cycles; (ii) fairly consistent within individuals; and (iii) unaffected by leak probability in any systematic way. On average, relative conditional bids are not significantly different from those in the truthful bidding equilibrium.*

Effect of Ex-ante Equality. We introduced the *two-sided* conditions to test for procedural fairness effects on bids of rational losers in SPA. Table 3 reports results of regressions of relative conditional bids in the *two-sided* treatments with a dummy for *two-sym*. The first model includes data for both experimental roles, A and B, the second and third for role A and B only, respectively. Contrary to Hypothesis 5, relative conditional bids are higher in *two-sym* than in *two-asym* in all models, significantly for role A.[14]

Result 4. *Relative conditional bids of rational losers in SPA are larger in* two-sym *than in* two-asym*, rejecting Hypothesis 5.*

Table 3: Ex-ante Fairness and Optimal Loser Bids

	(1) both roles	(2) role A	(3) role B
two-sym	0.0263	0.048**	0.0084
	(1.37)	(2.18)	(0.37)
_cons	0.561***	0.530***	0.588***
	(19.50)	(14.65)	(19.35)
N	422	201	221
p	0.172	0.0296	0.708

Note: Linear mixed effects regressions on rational losers' bids in the two-sided treatments with random intercept effects on participant nested in random effect on matching group. t statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Finally, if we look at rational loser bids of bidder 2 whose unconditional bid was optimal in the sense of $b_2(\emptyset, v_2) \leq v_2$, we find that 33.8% repeat their unconditional bid $b_2(\emptyset, v_2)$, 18.5% bid higher, and 47.8% lower.

4.1.4. Unconditional Bids

Table 4 reports separate mixed effects regressions of bids on transformed valuation $v' = v - 20$, rendering the interpretation of the estimated intercept more obvious. All estimations include only data from *baseline* and *one-sided*. Again, regressions include a

[14]First bidders gain the most in the cooperative equilibrium. Compared to the symmetric treatment, bidders in role A are more likely to be in the first-mover position in the asymmetric treatment, and may therefore behave more cooperatively (as second bidders) hoping that their partners will behave similarly.

random intercept effect on the participant nested in a random effect on matching group. Standard errors again rely on the Huber-White sandwich estimator. The first two models are for FPA only. The constant and effect on v' describe the bidding function in the *baseline*. Dummies *one-sided-1/4*, 1/2, and 3/4 measure differences in the intercept, interaction effects such as *one*-1/4 $\times v'$ measure differences in the reaction to changes in valuations.

4.1.5. Unconditional bids in FPA

According to the benchmark solution, the FPA estimations should identify an intercept of 20 and a slope in v' of 1/2, irrespective of role and leak probability. Model (1) estimates bidding functions of first movers in FPA. As all coefficients other than for intercept and v' are insignificant, there are no significant differences between *baseline* and leak-conditions. Wald tests confirm no significant differences between the different *one-sided* conditions. The intercept is significantly smaller than 20, and the reaction to changes in v' are significantly larger than 1/2 in all treatment conditions. [15]

Model (2) estimates bidding functions for unconditional bids of second movers. Contrary to first movers, there are some significant differences across probability conditions. While bidding behavior does not differ significantly, it varies in *one-sided-3/4*: here the intercept is significantly smaller than in *baseline* and *one*-1/2, whereas the slope is significantly smaller than in *baseline*.[16] Compared to the benchmark solution, for a positive leak probability the intercept is significantly smaller than 20.[17] The slope, on the other hand, is significantly larger than 1/2 in *baseline*, *one*-1/4 and *one*-1/2 (for *one*-3/4 there is no difference from 1/2).[18] The estimated bid functions in v' intersect with the benchmark solution in all conditions, except for second movers in *one*-3/4, with an intersection between 18.21 (second movers in *benchmark*) and 68.89 (second movers in

[15] In all treatment conditions: Wald-tests: H0: Intercept=20 vs. H1: Intcpt.$<$ 20: $p < .001$. H0: Slope $v' = 0.5$ vs. H1: $v' > 0.5$ $p < 0.001$.

[16] Wald-test for comparison of intercepts *one*-$3/4$ vs. *one*-$1/2$: $p = 0.037$.

[17] All Wald-test p-values smaller than 0.001

[18] Wald test p-values: *baseline*: $p < .001$, *one*1/4: $p < 0.001$, *one*-1/2: $p = 0.029$, *one*-3/4: $p = 0.190$.

one-1/2) (measured in v'). The estimated bid function for second movers in *one*-3/4 lies below the benchmark solution for all v.

Result 5. *Unconditional bids in FPA are mostly invariant in leak probability, as predicted by Hypothesis 2, with the exception of low unconditional bids made by second movers when the leak probability is very high.*

Table 4: Unconditional Bids

	(1)	(2)	(3)	(4)
	FPA		SPA	
	1st mover	2nd mover	1st mover	2nd mover
_cons	14.91***	18.07***	22.23***	21.54***
	(14.70)	(10.54)	(10.66)	(10.05)
one-sided 1/4	-0.190	-2.669	1.085	-1.966
	(-0.22)	(-1.52)	(0.36)	(-0.96)
one-sided 1/2	-0.643	-2.183	-2.799	0.816
	(-0.38)	(-1.19)	(-1.44)	(0.33)
one-sided 3/4	0.390	-4.421**	-2.229	3.025
	(0.37)	(-2.14)	(-0.83)	(1.08)
v'	0.633***	0.606***	1.008***	1.010***
	(20.54)	(24.61)	(28.02)	(28.18)
one-1/4 $\times v'$	-0.0136	-0.0242	-0.0549	0.00618
	(-0.55)	(-0.77)	(-0.96)	(0.16)
one-1/2 $\times v'$	0.00121	-0.0463	-0.0087	-0.0537
	(0.03)	(-1.19)	(-0.25)	(-1.12)
one-3/4 $\times v'$	0.0244	-0.0703*	-0.0234	-0.0915
	(0.72)	(-1.86)	(-0.67)	(-1.55)
N(#Subj)		1152(16)		
p	$< .001$	$< .001$	$< .001$	$< .001$

Note: Linear mixed effects regressions with random intercept effects on participant nested in effect on matching group. Regressions include data from *baseline* and *one-sided* conditions only. Transformed valuation $v' = v - 20$ used instead of v. t statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4.1.6. Unconditional bids in SPA

Models (3) and (4) in Table 4 report the results of estimations of aggregate bidding functions for first and second movers in SPA, respectively. Second movers, not being able to influence the bids of their partners, have a weakly dominant strategy to bid their true value. Indeed, Model (3) shows an intercept of approximately 20 and a slope of approximately 1 in all one-sided treatments, in line with truthful bidding.[19]

Recall that, despite a large heterogeneity of strategies, conditional bids in SPA are, *on average*, equivalent to truthful bidding. From Proposition 3 and truthful unconditional bidding by second movers, it follows that the optimal strategy of first movers is to bid their true valuation. Model (4) reveals that first movers' bids are indeed not significantly different from truthful bidding.[20]

Result 6. *Unconditional bids in SPA are not significantly different from truthful bidding. On average, first movers best respond to the distribution of conditional bids placed by rational losers.*

4.2. Aggregate outcomes

Figure 4 shows expected bidder surplus, revenue, and efficiency (total surplus) by auction mechanism and probability condition. Table 5 reports the results of mixed effects regressions of these variables on treatment dummies and Period. For all probability conditions except *baseline*, we calculated the expected outcome to avoid reporting results based on random draws made during the experimental sessions.[21] In *one-sided*, first (second) movers correspond to role A (B) participants in the experiment. In *two-asym*, the surplus is reported separately for first- and second movers: with probability 1/4 the B participant is first mover and with probability 3/4 it is participant A. For the *baseline* we report the surplus separately for the experimental roles.

The regressions reported in Table 5 are based on maximum likelihood estimations of linear mixed effect models of the form

$$y_{gijt} = \mathbf{x}_{gijt}\beta + r_g + u_i + e_j + \epsilon_{gijt}$$

[19]Wald tests on the joint hypotheses for intercept and slope result in $p > 0.114$ for all treatments.

[20]Wald tests on the joint hypotheses for intercept and slope result in $p > 0.170$ for all treatments.

[21]Suppose in SPA for *one-sided-1/2*, independent bids of A and B were 20 and 100, and the conditional bid of the latter was 20. Irrespective of the actual outcome in the experiment, we then used the expected revenue $0.5 \times 100 + 0.5 \times 20 = 60$.

where $\mathbf{x}$ is a vector of regressors, g indicates the matching group, i role A participant, j role B participant, and t the experimental round (period). Error terms u_i and e_j are each nested in r_g, and all error terms including ϵ are assumed to be orthogonal to each other and the regressors. The regressors are dummies for the five probability conditions, a dummy D_{SPA} for the second-price auctions and interaction terms, indicated by "$\times$." Standard errors are based on the Huber-White sandwich estimator. The bars in Figure 4 are the margins of the regressions in Table 5, and the 90% confidence intervals indicated by the whiskers are based on the Huber-White standard errors. We start analysis by comparing outcomes between FPA and SPA. These differences are indicated by interaction effects such as $D_{SPA}\times$one1/2 in Table 5.

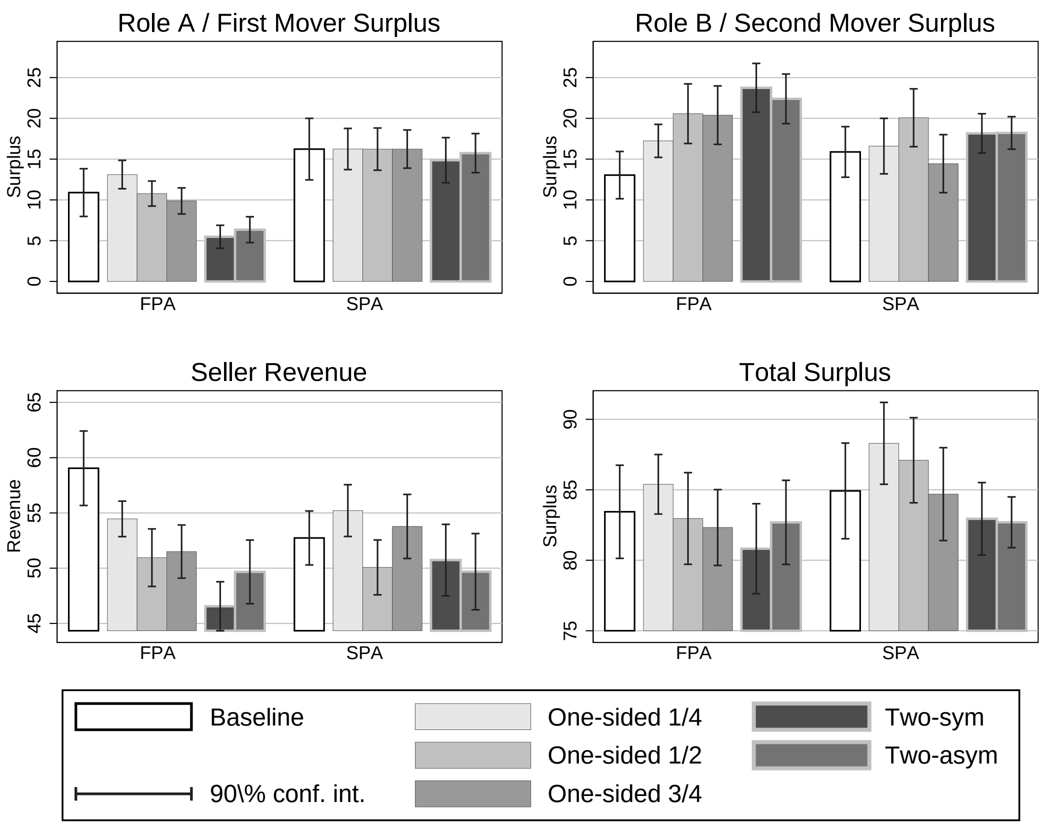

Figure 4: Outcomes

Note: Ex-ante expected outcomes (independent of random draws in experiment). Bars report margins of estimation results in Table 5, whiskers indicate 90% confidence interval. Bidder Surplus: in *baseline* by experimental role (A or B), in all other conditions separately for first and second movers.

Table 5: Outcomes

	(1) Surplus FM/A	(2) Surplus SM/B	(3) Revenue	(4) Efficiency
_cons	11.16***	12.01***	57.92***	81.34***
	(6.81)	(7.06)	(29.37)	(37.84)
one-sided 1/4	2.210	4.195*	-4.582**	1.952
	(0.94)	(1.87)	(-2.11)	(0.64)
one-sided 1/2	-0.119	7.531**	-8.093***	-0.475
	(-0.05)	(2.50)	(-4.45)	(-0.18)
one-sided 3/4	-1.022	7.353***	-7.539***	-1.115
	(-0.46)	(3.01)	(-3.52)	(-0.37)
two-sym	-5.417**	10.70***	-12.49***	-2.621
	(-2.44)	(4.07)	(-7.26)	(-1.12)
two-asym	-4.549**	9.349***	-9.380***	-0.751
	(-2.02)	(3.46)	(-3.48)	(-0.26)
$D_{SP}\times$baseline	5.330***	2.842*	-6.311***	1.481
	(3.51)	(1.87)	(-3.10)	(0.64)
$D_{SP}\times$one-1/4	3.133**	-0.640	0.750	2.904
	(1.98)	(-0.30)	(0.46)	(1.44)
$D_{SP}\times$one-1/2	5.449***	-0.498	-0.878	4.133*
	(3.36)	(-0.18)	(-0.43)	(1.71)
$D_{SP}\times$one-3/4	6.358***	-5.949**	2.272	2.370
	(4.16)	(-2.17)	(1.06)	(0.98)
$D_{SP}\times$two-sym	9.386***	-5.586***	4.179**	2.122
	(5.67)	(-2.80)	(1.99)	(1.13)
$D_{SP}\times$two-asym	9.389***	-4.177**	0.0208	0.0072
	(6.40)	(-2.15)	(0.01)	(0.00)
N / # Groups		3456(24)		
p	$< .0001$	$< .0001$	$< .0001$	$< .0001$

Note: Linear mixed effects regressions with random intercept effects on role A and B participant nested in effect on matching group. t statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. D2nd is an indicator variable for the second price rule and "$\times$" indicates an interaction effect. Efficiency is measured as the value of the auction winner. Not reported: separate control variables for Period in *baseline*, *one-sided*, and *two-sided* conditions (all three insignificant).

Table 6 complements Table 5 by reporting results of regressions of outcomes in the *one-sided* treatments, this time taking the probability of a leak as a continuous independent variable. The results of this analysis confirm Hypothesis 4:

Result 7. *In FPA, second mover surplus significantly increases whereas all other outcome variables significantly decrease with increasing leak probability.*

Result 3 in Section 4 stated that bids in SPA, *on average*, are approximately equivalent

Table 6: Effect of Leaking Probability on Outcomes

	First-Price Auction			
	(1) Surplus FM/A	(2) Surplus SM/B	(3) Revenue	(4) Efficiency
Prob{leak}	-6.406***	6.321**	-6.034*	-6.121*
	(-2.69)	(2.03)	(-1.92)	(-1.66)
Period	-0.109**	0.114	0.0996	0.0918
	(-2.56)	(1.59)	(1.48)	(1.10)
_cons	15.49***	14.35***	53.73***	83.93***
	(9.03)	(8.61)	(25.36)	(31.00)
N / # Groups		864(12)		
p	0.0081	0.0579	0.0490	0.0911
	Second-Price Auction			
	(5) Surplus FM/A	(6) Surplus SM/B	(7) Revenue	(8) Efficiency
Prob{leak}	0.0606	-4.320	-3.349	-7.215**
	(0.02)	(-0.75)	(-0.75)	(-1.99)
Period	-0.0270	0.0183	0.0413	0.0298
	(-0.27)	(0.20)	(0.65)	(0.31)
_cons	15.73***	19.05***	54.13***	88.75***
	(6.95)	(5.66)	(26.14)	(33.04)
N / # Groups		864(12)		
p	0.963	0.751	0.685	0.109

Note: Data from *one-sided* conditions only. Linear mixed effects regressions with random intercept effects on role A and B participant nested in effect on matching group. Efficiency is measured as the value of the auction winner. t statistics in parentheses. * $p < 0.1$, **$p < 0.05$, *** $p < 0.01$.

to truthful bidding. Subsequently, aggregate outcomes do not vary significantly with leak probability (cf. Table 1 and Figure 1). Note, however, that although first bids are not systematically different from the first bidder's value, there is substantial variance in the bids. Deviations may increase or decrease both bidders' payoffs, but have an unequivocal negative effect on efficiency, which is amplified by leaks if second bidders also deviate. This is reflected in the negative effect of leak probability on efficiency.

Result 8. *In SPA, bidder surplus and seller revenue do not react systematically to changes in the leak probability. Efficiency significantly decreases as leak probability goes up.*

We saw that bidding strategies in both FPA and SPA are not sensitive to the leak probability. The last two results spell out the implications for expected payoffs: In FPA, but not in SPA, *realized* leaks allow the second bidder to win when having a lower value and to reduce the price when winning with a higher value. Considering that without leaks, bids in FPA are above the equilibrium prediction—consistent with previous experiments—the comparison of FPA and SPA follows directly, and is summarized in our final result.

Result 9. *Without leaks, seller revenue is significantly larger in FPA. Bidders earn significantly more in SPA (for both roles A and B). Efficiency is higher in SPA, though not significantly. With leaks, seller revenue is no longer higher in FPA, and for high leak probabilities is even higher in SPA (significantly so only in two-sym, where the probability of a leak is one). The opposite holds for second bidders' surplus, which is no longer higher in SPA and becomes significantly higher in FPA for high leak probabilities. First bidders' payoffs and efficiency are higher in SPA for all leak probabilities, though the latter is generally not significant.*

5. Conclusion

The most prominent auction formats are the first-price sealed-bid auction and the second-price sealed bid auction or the strategically-equivalent (with independent private values) ascending bid auction. The experimental evidence strongly suggests that, in the case of independent private values, first-price auctions generate higher seller revenue, while second-price auctions are more efficient.[22] Our theoretical analysis reveals that these stylized empirical facts may not hold when information about one's bid may be revealed to her opponents. Moreover, comparative statics comparisons across auction mechanisms are not unequivocal due to the multiplicity of equilibria in second-price auctions.

The experimental results in the first-price treatments are as predicted. Unconditional bids are not affected by the leak probability, but realized leaks increase the second mover's payoff while reducing the first mover's payoff, seller revenue, and overall efficiency. We observe a large variance in second movers' strategies, corresponding to the different (pure-strategies) equilibria. However, bidding behavior is, on average, equivalent to truthful bidding, and therefore the probability of leak doesn't have a systematic effect on expected seller revenue. Nonetheless, due to the pronounced effect in first-price auctions, leaks affect the comparison between the two auction mechanisms. Indeed, the first-price mechanism is no longer favorable from the point of view of the seller and in our symmetric treatment, where the probability of a leak is one, the second-price mechanism provides a higher revenue to the seller.[23]

Our behavioral conclusions are in line with those of Andreoni et al. (2007), who similarly manipulated information that bidders hold about their opponents. In their experiment, four bidders learn the realized *valuations* rather than the *bids* of none, one, or all three other bidders. Thus, their setting does not invoke the strategic adjusting of unconditional bids in second-price auctions that drives the multiple equilibria, which are at the core of our theoretical and experimental analysis. Notwithstanding, we share some of Andreoni et al.'s (2007) conclusions, namely that dominated behavior is rare and decreases with experience; that behavior is consistent with the comparative statics in first-price auctions; and that a substantial proportion of second movers who discover

[22]Risk aversion is able to rationalize both these phenomena.

[23]Explicit collusion may also eliminate the revenue dominance of first-price auctions (Llorente-Saguer and Zultan, 2014; Hu et al., 2011; Hinloopen and Onderstal, 2014)

that they have practically no chance of gaining from winning the auction choose to bid above their own value, consistent with spiteful motives. Unlike Andreoni et al. (2007), we also observe a substantial proportion of cooperative bidding. This difference can be explained by a fundamental difference between the two settings: rational losers in our experiment *know* that the high bid is above their valuation, whereas in Andreoni et al. (2007) this is only true if other bidders follow the dominant strategy of bidding their valuations. In the latter case, possible bid shading by others deter cooperative bidding.[24]

In summary, it can be concluded that informational leaks, whereby later bidders can react to earlier bids, can be crucial when comparing bidding mechanisms such as first-price and second-price auctions. For first-price auctions, benchmark bidding is unaffected, but leaks do affect allocation outcomes. For second-price auctions leaks result in a large multiplicity of equilibria, in which truthful bidding, spiteful, and cooperative inclinations induce salient focal points.[25] While theoretically, fairness concerns could affect which of those equilibria bidders prefer to coordinate on, we do not find evidence to this effect.

One straightforward extension of our model is the introduction of marginal bidding costs. Rational losers would then always refrain from bidding, reducing the second price auction equilibria to the cooperative ones. In our experiments, cognitive costs associated with evaluating a different conditional bid than the unconditional one can be interpreted as such marginal costs. Our result that only about one third of rational loser bids repeat an otherwise rationalizable unconditional bid therefore suggests that marginal costs play a negligible role in bidding.

Other interesting questions arise from endogenizing leak probability by introducing espionage, strategic leaks or both. In our setting, incentives for engaging in espionage are stronger in FPA than SPA. Further research, both theoretical and experimental, may

[24]Roth and Ockenfels (2002), for example, suggest that expecting bid shading from others in second-price auctions provides a (partial) explanation for sniping in online auctions.

[25]Even without leaks, second-price auctions have multiple equilibria but in weakly dominated strategies, cf. Plum (1992)

establish whether this holds if leaks are endogenous.

References

ANDREONI, J., Y.-K. CHE, AND J. KIM (2007): "Asymmetric information about rivals' types in standard auctions: An experiment," *Games and Economic Behavior*, 59, 240–259.

ARIELY, D., A. OCKENFELS, AND A. E. ROTH (2005): "An experimental analysis of ending rules in Internet auctions," *RAND Journal of Economics*, 36, 891–908.

AVERY, C. (1998): "Strategic jump bidding in English auctions," *Review of Economic Studies*, 65, 185–210.

BERGEMANN, D. AND M. PESENDORFER (2007): "Information structures in optimal auctions," *Journal of Economic Theory*, 137, 580–609.

BOLTON, G. E., J. BRANDTS, AND A. OCKENFELS (2005): "Fair Procedures: Evidence from games involving lotteries," *The Economic Journal*, 115, 1054–1076.

BOLTON, G. E. AND A. OCKENFELS (2000): "ERC: A Theory of Equity, Reciprocity, and Competition," *The American Economic Review*, 90, 166–193.

BULOW, J. AND P. KLEMPERER (2009): "Why do sellers (usually) prefer auctions?" *The American Economic Review*, 99, 1544–1575.

CASSADY, R. (1967): *Auctions and auctioneering*, Univ of California Press.

CHARNESS, G. AND M. RABIN (2002): "Understanding Social Preferences with Simple Tests," *The Quarterly Journal of Economics*, 117, 817–869.

DANIEL, K. D. AND D. A. HIRSHLEIFER (1998): "A Theory of Costly Sequential Bidding," *University of Michigan Business School Working Paper*.

ESŐ, P. AND B. SZENTES (2007): "Optimal information disclosure in auctions and the handicap auction," *The Review of Economic Studies*, 74, 705–731.

FANG, H. AND S. MORRIS (2006): "Multidimensional private value auctions," *Journal of Economic Theory*, 126, 1–30.

FISCHBACHER, U. (2007): "z-Tree: Zurich Toolbox for Ready-made Economic Experiments," *Experimental Economics*, 10, 171–178, the experiment was programmed and conducted with the software z-Tree (Fischbacher 2007).

FISHMAN, M. J. (1988): "A theory of preemptive takeover bidding," *The Rand Journal of Economics*, 88–101.

FONSECA, M. A. (2009): "An experimental investigation of asymmetric contests," *International Journal of Industrial Organization*, 27, 582–591.

GERSHKOV, A. (2009): "Optimal auctions and information disclosure," *Review of Economic Design*, 13, 335–344.

GREINER, B. (2004): "An Online Recruitment System for Economic Experiments," in *Forschung und wissenschaftliches Rechnen 2003*, ed. by K. Kremer and V. Macho, Göttingen: Gesellschaft für Wissenschaftliche Datenverarbeitung, vol. 63 of *GWDG Bericht*.

GÜTH, W., M. V. LEVATI, AND M. PLONER (2013): "Does Procedural Fairness Crowd Out Other-Regarding Concerns? A Bidding Experiment," *Journal of Institutional and Theoretical Economics JITE*, 169, 433–450.

HINLOOPEN, J. AND S. ONDERSTAL (2014): "Collusion and the choice of auction: An experimental study," *mimeo*.

HOFFMANN, M. AND G. ROTA-GRAZIOSI (2012): "Endogenous timing in general rent-seeking and conflict models," *Games and Economic Behavior*, 75, 168–184.

Hu, A., T. Offerman, and S. Onderstal (2011): "Fighting collusion in auctions: An experimental investigation," *International Journal of Industrial Organization*, 29, 84 – 96, ¡ce:title¿Special Issue: Experiments in Industrial Organization¡/ce:title¿.

Kagel, J. H. (1995): "Auctions: A Survey of Experimental Research," in *The Handbook of Experimental Economics*, ed. by J. H. Kagel and A. E. Roth, Princeton University Press, chap. 7, 501–585.

Kaplan, T. R. (2012): "Communication of preferences in contests for contracts," *Economic Theory*, 51, 487–503.

Kaplan, T. R. and S. Zamir (2000): "The strategic use of seller information in private-value auctions," *Center for Rationality and Interactive Decision Theory Discussion paper*.

——— (2014): "Advances in Auctions," in *Handbook of Game Theory*, ed. by P. Young and S. Zamir, Elsevier, vol. 4.

Kim, J. and Y.-K. Che (2004): "Asymmetric information about rivals' types in standard auctions," *Games and Economic Behavior*, 46, 383–397.

Krawczyk, M. and F. LeLec (2010): "Give me a chance! An experiment in social decision under risk," *Experimental Economics*, 13, 500–511.

Landsberger, M., J. Rubinstein, E. Wolfstetter, and S. Zamir (2001): "First–price auctions when the ranking of valuations is common knowledge," *Review of Economic Design*, 6, 461–480.

Levin, D., J. Peck, and A. Ivanov (2014): "Separating Bayesian Updating from Non-Computational Reasoning: An Experimental Investigation," *Mimeo*.

Llorente-Saguer, A. and R. Zultan (2014): "Auction Mechanisms and Bidder Collusion: Bribes, Signals and Selection," *mimeo*.

MILGROM, P. R. AND R. J. WEBER (1982): "A Theory of Auctions and Competitive Bidding," *Econometrica*, 50, 1089–1122.

OCKENFELS, A. AND A. E. ROTH (2006): "Late and multiple bidding in second price Internet auctions: Theory and evidence concerning different rules for ending an auction," *Games and Economic Behavior*, 55, 297–320.

PERSICO, N. (2000): "Information acquisition in auctions," *Econometrica*, 68, 135–148.

PLUM, M. (1992): "Characterization and computation of nash-equilibria for auctions with incomplete information," *International Journal of Game Theory*, 20, 393–418.

ROTH, A. E. AND A. OCKENFELS (2002): "Last-Minute Bidding and the Rules for Ending Second-Price Auctions: Evidence from eBay and Amazon Auctions on the Internet," *American economic review*, 92, 1093–1103.

A. Derivation of Corollary 1

For bidder 1 the expected surplus depends on v_1 via

$$\pi_1(v_1) = [p\frac{v_1}{2} + (1-p)v_1](\frac{v_1}{2}) = (1-\frac{p}{2})\frac{v_1^2}{2}.$$

Thus bidder 1's expected profit is

$$E[\pi(v_1)] = (1-\frac{p}{2})\frac{1}{2}E[v_1^2] = (1-\frac{p}{2})\frac{1}{2}\int_0^1 v_1^2 dv_1 = \frac{1}{6} - \frac{p}{12}.$$

When uninformed, bidder 2's expected surplus is $\pi_2(v_2) = \frac{v_2^2}{2}$. Ex-ante this yields $E[\pi_2(v_2)] = E[\frac{v_2^2}{2}] = \frac{1}{6}$. When bidder 2 is informed about b_1 and $v_2 \geq \frac{1}{2}$, bidder 2 expects to earn $v_2 - \frac{1}{4}$, whereas for $v_2 \leq \frac{1}{2}$, informed bidder 2 can expect v_2^2. Ex-ante informed bidder 2 expects $\int_0^{\frac{1}{2}} v_2^2 dv_2 + \int_{\frac{1}{2}}^1 (v_2 - \frac{1}{4})dv_2 = \frac{1}{24} + \frac{1}{2} - \frac{1}{8} - (\frac{1}{4} - \frac{1}{8}) = \frac{7}{24}$. Thus, bidder 2's total expected profit is $p\frac{7}{24} + (1-p)\frac{1}{6} = \frac{1}{6} + \frac{p}{8}$.

When F is uniform, with probability $1-p$ revenue equals $\max\{v_1, v_2\}/2$ as usual. With probability p, however, the revenue equals $v_1/2$, and therefore total expected revenue is

$$(1-p)E[\frac{\max\{v_1, v_2\}}{2}] + pE[\frac{v_1}{2}] = (1-p)\cdot\frac{1}{3} + p\frac{1}{4} = \frac{1}{3} - \frac{p}{12}.$$

Since for efficiency, the sum of all expected surpluses of the seller and both bidders should be $\frac{2}{3}$, the efficiency loss is $\frac{2}{3} - (\frac{1}{3} - \frac{p}{12}) - (\frac{1}{6} - \frac{p}{12}) - (\frac{1}{6} + \frac{p}{8}) = \frac{p}{6} - \frac{p}{8} = \frac{p}{24}$. We summarize the above in the following Corollary.

B. Outcomes in SPA

We derive bidder surplus, seller revenue and total efficiency for the three focal equilibria in SPA.

B.1. Outcomes in SP-Truthtelling

In the SP-Truthtelling equilibrium neither bids of bidder 1 nor bidder 2 are affected by the leak probability and therefore all ex-ante expected outcomes are as in the standard simultaneous case.

B.2. Outcomes in SP-Spiteful Bidding

For F uniform and spiteful bidding, we have $b_1(v_1) = \frac{v_1}{1+p}$. In the SP-Spiteful equilibrium, bidder 1's expected surplus is

$$p \int_0^1 \frac{v_1}{1+p}(v_1 - \frac{v_1}{1+p})dv_1 + (1-p) \int_0^1 \frac{v_1}{1+p} \left(v_1 - \frac{v_1}{2(1+p)} \right) dv_1 = \frac{1}{6(1+p)},$$

and bidder 2's expected surplus is

$$p \cdot \int_0^1 (1 - \frac{v_1}{1+p})(1 - \frac{v_1}{1+p}) \frac{1}{2} dv_1 + (1-p)(1+p) \int_0^{\frac{1}{1+p}} (1-b_1)^2 \frac{1}{2} db_1 = \frac{1+3p(1+p)}{6(1+p)^2}.$$

The Seller's revenue is

$$p \frac{1}{2(1+p)} + (1-p) \int_0^{v_1} \left[\frac{v_1}{1+p} \cdot \frac{v_1}{2(1+p)} + (1 - \frac{v_1}{1+p}) \frac{v_1}{1+p} \right] dv_1 = \frac{1+2p}{3(1+p)^2},$$

and thus, the efficiency loss is

$$\frac{p^2}{6(1+p)^2}.$$

B.3. Outcomes in SP-Cooperation

In the SP-Cooperation equilibrium, bidder 1's expected surplus is

$$\begin{aligned} p \cdot \int_0^{1-p} \frac{v_1}{1-p} \cdot v_1 dv_1 + p^2 \cdot \frac{2-p}{2} \\ + (1-p) \left[p((1 - \frac{p}{2}) - \frac{1}{2}) + (1-p) \int_0^1 \int_0^{b_1} (b_1(1-p) - b_2) db_2 db_1 \right] \\ = \frac{1+p+p^2}{6}, \end{aligned}$$

and bidder 2's expected surplus equals

$$p \cdot \int_0^{1-p} (1 - \frac{v_1}{1-p})(1 - \frac{v_1}{1-p})\frac{1}{2} dv_1 + (1-p)(1-p) \cdot \frac{1}{6} = \frac{1-p}{6}.$$

The expected revenue is

$$p \cdot \int_0^{1-p} (1 - \frac{v_1}{1-p})\frac{v_1}{1-p} dv_1 + (1-p)(\frac{p}{2} + \frac{1-p}{3}) = \frac{1-p^2}{3}.$$

C. Translated Instructions

This is a translation of the German instructions for the first-price mechanism. Where instructions differed in the second-price mechanism, we indicate this by [`SP`: different text].

Instructions

Welcome to this experiment on economic behavior. Your final euro payoff will depend on your decisions, those of other participants and random draws. Please read these instructions carefully, switch off your phone, and do not communicate with other participants. If you have a problem or question, please raise your arm and wait for a supervisor to help you.

In the experiment, monetary amounts are denominated in *ECU* (for *experimental currency unit*. The experiment consists of several rounds. Following the final round, we will randomly select **five**. The sum of amounts you earned in those five rounds will then be added up, exchanged into euro and paid to you in cash. The exchange will be made at the following rate: **1 ECU = €0.13**

In every round you will interact with another participant than in the previous round. This participant will be chosen at random. No other participant will learn something about your identity from us. The instructions are identical for all participants.

General Procedure

In every round you and the other participant take part in an auction. Each one of you bids for a token. This token has a monetary value for each one of you. In the following, we call this amount "**value**". Your *value* and the *value* of the other participant are determined randomly at the beginning of every round. The value is a random amount between 20.00 and 120.00 (with two decimal points), where every possible realization is equally likely. The two values for you and the other participant are determined separately and independently of each other. It is therefore highly unlikely for the two to coincide. You will only be informed about your **own** value.

In every round both participants submit a **bid**. A **bid** can be any number between 0.00 and 140.00 (with two decimal points). The one with the **higher** bid wins the auction, earns his **value** and pays his bid [`SP`: the bid of the other participant]. The participant with the lower bid earns nothing and pays nothing.

How to Bid

First, both **simultaneously** submit a **First Bid**. However, these **First Bids** are not always relevant. With a known probability (see below), **one** of the participants will learn the **First Bid** of the **other** participant and can submit a new bid. This new bid, which we will call **Second Bid**, can be any number between 0.00 and 149.00, irrespective of the First Bids. If someone was able to submit a new bid, then this **Second Bid** is his relevant bid. Otherwise, the First Bid is relevant. However, it never happens that both can submit a Second Bid.

With known probability p it is you who can observe the other participant's First Bid and submit a Second Bid. With probability q it is the other participant who can see your First Bid and submit a Second Bid. With residual probability $1 - p - q$ no one can submit a new bid and, thus, only the First Bids are relevant. In some rounds both $p = 0$ and $q = 0$, in others only $q = 0$ or $p = 0$ or probabilities are such that $p + q = 1$ and therefore $1 - p - q = 0$. You are informed about the probabilities p, q, and $1 - p - q$ at the beginning of every round.

Identical Bids

The participant with the higher relevant bid wins the auction. Should the two relevant bids be identical, then the winner is determined as follows: If only both First Bids are relevant, the winner is randomly determined (each one with equal probability). Otherwise, the participant whose Second Bid is relevant, wins the auction.

Outcome

- The participant with the smaller **relevant** bid earns 0 ECU.
- The participant with the larger **relevant** bid earns his **value** minus his **relevant bid**.

Losses

Please note that you will make a loss if you win the auction and your relevant bid exceeds your **value**. In case you make losses, we substract them from your fixed payments (€2.50 show-up fee and €2.50 for answering the control questionnaire). If these amounts do not suffice, you will have to work off the remainder.

Control Questions

Procedure

The procedure in the experiment will slightly differ from what we explained above. As described, first both participants submit a First bid. Then a random draw decides with known probabilities p, q, and $1 - p - q$ whether and, if so, who can submit a Second Bid.

However, you will only be informed about the outcome of this random draw at the end of the round. Instead, irrespective of this outcome, we will inform you about the other's first bid and ask you how you would behave, should you be able to submit a Second Bid. Of course, this Second Bid is only relevant when the random draw actually determined that you can submit a second bid. More specifically,

1. You are informed about your own value.
2. You are informed about probabilities $1 - p - q$, p, and q.
3. Both participants simultaneously determine their First Bid.
4. The Computer randomly determines according to these probabilities whether someone and, if so, who can submit a Second Bid. **You will not be informed about the result of this random draw before the end of the round.**
5. If the probability that you can submit a Second Bid is positive,
   - you are informed about the First Bid of the other participant
   - and can submit a Second Bid.
6. The round ends and you are informed about:
   - The outcome of the random draw, i.e., which bids are relevant,
   - who has won the auction, and
   - your outcome in ECU.

Do you have any questions? Please do not hesitate to ask one of the experimenters.